

CHANNEL OPTIMIZATION SYSTEM

Inventor: Jingdong Lin
32 Fern Pine
Irvine, California 92618

Assignee: Lucent Technologies Inc.
600 Mountain Avenue
Murray Hill, New Jersey 07974-0636

06374632662 4223100

CERTIFICATE OF EXPRESS MAIL

I hereby certify that this correspondence, including the attachments listed, is being deposited with the United States Postal Service, Express Mail - Post Office to Addressee, Receipt No. ELO538674694US, in an envelope addressed to Commissioner of Patents and Trademarks, Washington, D.C. 20231, on the date shown below.

12-21-00 Stephanie Stafford
Date of Mailing Typed or printed name of person mailing
Stephanie Stafford
Signature of person mailing

Hitt Gaines & Boisbrun, P.C.
P.O. Box 832570
Richardson, Texas 75083
(972) 480-8800

CHANNEL OPTIMIZATION SYSTEM

TECHNICAL FIELD OF THE INVENTION

The present invention is directed, in general, to signal processing and, more specifically, to a channel optimization system and method of separating and encoding signals associated with a communications channel of a telecommunications network.

BACKGROUND OF THE INVENTION

With the development of broadband telecommunication systems, the use of data channels to carry voice signals is becoming widespread. The voice signals may be transmitted over a variety of medium and employing different protocols. For instance, the transfer of voice signals has become increasingly ubiquitous, employing a vast array of technologies such as Digital Subscriber Line Service and over a vast array of networks such as Internet Protocol based packet networks. Moreover, there is every reason to believe that this trend will continue.

One measurement of an efficiency associated with a signal traversing a communications channel of a telecommunications network

10
11
12
13
14
15
16
17
18
19

is the bit error rate (BER). The BER may be defined as the percentage of received bits having errors relative to the total number of bits received during a transmission. Generally speaking, the BER associated with the transmission of voice signals is about 5 10^{-3} and of non-voice data signals about 10^{-7} . Thus, data signals are typically more sensitive to errors than voice signals. Although voice and data signals have different BER tolerances and sensitivity levels, voice and data signals have been processed in the same manner in telecommunication systems of the past, at least insofar as the requirements associated with the BER are concerned. While the telecommunications systems presently employed are less complex to implement, requiring voice signals and data signals to abide by equivalent transport techniques (even though the requirements may be different) is not the most efficient use of the bandwidth of a telecommunications network.

20

In conjunction with the transfer of information across the telecommunications network, telecommunications systems often employ modulation techniques to more efficiently transfer the information across a communications channel of the network. For instance, quadrature amplitude modulation (QAM) is one modulation technique that carries the information bits in both the in-phase and quadrature direction and shifts the signal band around a single carrier frequency. In a modulation technique such as QAM, the unit

of information transferred is called a "symbol", which may in turn represent multiple bits of information. The number of bits represented by a symbol is referred to as its "symbol density."

A theoretical channel capacity of a communications channel associated with a telecommunications network can be derived by the well recognized Shannon's formula. While Shannon's theorem describes the theoretical capacity of a communications channel, for a given modulation technique there is a disparity between the attainable channel capacity and the theoretical capacity. The difference between the theoretical and attainable channel capacity is represented by the signal-to-noise ratio (SNR) gap and it determines how many bits can be loaded to a symbol for a particular modulation technique such as QAM.

Additionally, for reasons that will become more apparent, the SNR gap is related to the BER associated with the information traversing the communications channel and, as mentioned above, has a bearing on the maximum symbol constellation density allowable. In a situation where the SNR gap is quite large, each transmitted symbol conveys less information to accommodate the larger gap. (i.e., the attainable channel capacity is further removed from the theoretical channel capacity.) Thus, it is important to pack as much information as possible into a symbol (or for that matter any representation of information traversing a communications channel)

to more effectively maximize the bandwidth of the telecommunications network.

Accordingly, what is needed in the art is a system and method that more efficiently manages the transmission of information
5 (e.g., voice and data signals) across a telecommunications network that overcomes the deficiencies in the prior art.

SUMMARY OF THE INVENTION

To address the above-discussed deficiencies of the prior art, the present invention provides a channel optimization system for use with a communications channel and method of separating and 5 encoding signals associated with the communications channel. In one embodiment, the channel optimization system includes an assorter that receives first and second signals having disparate transmission characteristics and selects one of the first and second signals. The channel optimization system also includes a translator, coupled to the assorter, that encodes the selected one of the first and second signals into a symbol representation as a function of a transmission characteristic associated therewith.

00000000000000000000000000000000

15

20

The present invention introduces, in one aspect, a channel optimization system that processes multiple signals traversing a communications channel of a telecommunications network in a different manner. In conjunction therewith, the assorter of the channel optimization system separates the signals by, for instance, the bit error rate (BER) transmission characteristics of the signals. The translator of the channel optimization system then encodes the signals for insertion on to the communications channel. As a result, the channel optimization system more efficiently

utilizes the available bandwidth of the communications channel of the telecommunications network.

The foregoing has outlined, rather broadly, preferred and alternative features of the present invention so that those skilled in the art may better understand the detailed description of the invention that follows. Additional features of the invention will be described hereinafter that form the subject of the claims of the invention. Those skilled in the art should appreciate that they can readily use the disclosed conception and specific embodiment as a basis for designing or modifying other structures for carrying out the same purposes of the present invention. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the invention in its broadest form.

10
CONTINUED
- 12 -

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

5 FIGURE 1 illustrates a system level diagram of an embodiment of a telecommunications network providing an environment for the application of the principles of the present invention;

10 FIGURE 2 illustrates a block diagram of an embodiment of a transmitter and receiver constructed according to the principles of the present invention;

15 FIGURE 3 illustrates a block diagram of an embodiment of a channel optimization system constructed according to the principles of the present invention;

20 FIGURE 4 illustrates a two dimensional vector symbol constellation diagram of an embodiment of a bit-to-symbol map constructed in accordance with the principles of the present invention;

FIGURE 5A illustrates a flow diagram of an embodiment of an initialization of a channel optimization system in accordance with the principles of the present invention.

FIGURE 5B illustrates a flow diagram of an embodiment of an operation of a channel optimization system in accordance with the principles of the present invention; and

FIGURES 6A, 6B and 6C illustrate graphical representations
5 demonstrating selected advantages in accordance with the principles of the present invention.

06246352-122100

DETAILED DESCRIPTION

Referring initially to FIGURE 1, illustrated is a system level diagram of an embodiment of a telecommunications network 100 providing an environment for the application of the principles of the present invention. The telecommunications network 100 includes voice and data networks 105, 110 coupled to a central office 120. The central office 120 is then coupled via a twisted pair wire 125 which may carry a Digital Subscriber Line (DSL) service to a remote terminal hub 130. The remote terminal hub 130 then splits the voice and data signals for delivery to the voice terminals 140, either plain old telephone stations (POTS) or derived voice service terminals, and computer terminals 150, respectively. Of course, the telecommunications network 100 is only one example of a network that may benefit from the principles of the present invention. Those skilled in the art, therefore, should understand that other network configurations are well within the broad scope of the present invention.

For presentation purposes, the voice network 105 transmits the voice signals and the data network 110 transmits the data signals. The voice and data signals have different transmission characteristics and requirements associated therewith. In the central office 120, after a certain level of call processing has

occurred, the voice and data signals are then processed to derive and apply an appropriate symbol representation in a manner described with respect to the following FIGUREs. The voice and data signals are then transmitted from the central office 120 over
5 the twisted pair wire 125 to the remote terminal hub 130.

As stated above, the remote terminal hub 130 receives the voice and data signals from the twisted pair wire 125 and performs a variety of signal processing tasks, possibly analogous to the signal processing tasks performed in the central office 120. The remote terminal hub 130 then sends the voice signals to the voice terminals 140 and the data signals to the computer terminals 150.
10
15

A channel capacity (C) of the twisted pair wire 125 or any subchannel thereof, or for that matter of any other given transmission medium, has a theoretical rate of error-free extractable bits-per-second signal throughput. The theoretical throughput is a function of the given channel's or subchannel's signal-to-noise ratio (SNR), as given by Shannon's theorem:
20

$$C = \log_2 (1 + \text{SNR}).$$

As previously mentioned, however, for any given telecommunications system employing a modulation technique, there is a disparity between the theoretical channel capacity and the
20

attainable channel capacity. The channel capacity is affected by factors such as the modulation technique employed and the bit error rate (BER) associated with the information traversing the communications channel. For example, in quadrature amplitude modulation (QAM), the channel capacity is:

$$C = \log_2 (1 + 3/\Delta^2 \times SNR).$$

gap," or more simply, just the "gap". The term " Δ^2 " is related to the BER desired error rate. As can be deduced from the above equation, as the desired BER (expressed in terms of an increasing value for Δ , as to be detailed below) becomes more rigorous, the product of the inverse of the SNR gap and the SNR of the transmission medium decreases, and hence the channel capacity decreases. The channel capacity may be interpreted as the throughput of a telecommunications network taking into account the SNR gap, which is in turn depends on the BER of the transmitted information.

As previously mentioned, the SNR gap is a function of the required BER, represented as "p", of the information traversing the communications channel. The relationship can be expressed in a formula as set forth below:

$$p = \frac{2}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{x^2}{2}} dx$$

For exemplary BER values, the corresponding values of Δ and the SNR gap are illustrated in table as set forth below.

BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
Δ	2.577	3.287	3.891	4.418	4.892	5.333
Gap (dB)	3.45	5.56	7.03	8.13	9.02	9.77

TABLE 1

5

Both the SNR and the SNR gap will also determine how many bits can be loaded to a symbol for any modulation technique employed (e.g., QAM or of any other modulation technique). For example, in a QAM system, the maximum number of bits that can be loaded to a QAM symbol is usually calculated as follows:

$$b = \log_2(1 + 10^{\frac{G}{10}})$$

where,

15

$$G = \text{SNR} - \text{SNR gap} - \text{margin} + \text{CodingGain}.$$

The "margin" is included to provide a margin of error to compensate for, among other things, unexpected or signal degradation phenomena. The "CodingGain" generally represents the equivalent gain of the SNR in decibels (dBs) based upon certain well known error control algorithms.

100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
73
72
71
70
69
68
67
66
65
64
63
62
61
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0

As demonstrated by the foregoing formulas, more bits can be loaded per symbol if the SNR gap (which is in turn a function of the BER of the information traversing the communications channel) is smaller. More bits loaded per symbol can lead to a more efficient telecommunications network providing a motivation for the discovery of the principles of the present invention.

Turning now to FIGURE 2, illustrated is a block diagram of an embodiment of a transmitter and receiver constructed according to the principles of the present invention. The transmitter and receiver may be associated with a communications system such as the central office 120 or remote terminal hub 130 of the telecommunications network 100 illustrated and described with respect to FIGURE 1.

Data signals (via a data bit source 210) and voice signals (via a voice bit source 215) enter the transmitter and are merged together in bit merge and framer subsystem 220. For instance, the merging may be accomplished by the interleaving of frames or sub-frames of voice and data signals on the basis of a time slice.

Appropriate header information indicating the type of merged signal
(i.e., voice or data) may also be included with the merged
information. The merged bits are then processed by a forward error
correction coding subsystem 230 using conventional forward error
correction coding algorithms, which are then passed on to a bit-to-
symbol mapping subsystem 240. The bit-to-symbol mapping subsystem
240 deciphers between disparate types of signals (i.e., voice and
data signals) and separates the signals accordingly. In
conjunction therewith, the bit-to-symbol mapping subsystem 240 maps
the signals into symbols as a function of transmission requirements
associated with the different types of signals.

A modulator 250 of the transmitter modulates the symbols using, for instance, Fast Fourier Transform operations in association with a modulation technique such as QAM as is understood by those skilled in the art. Thereafter, a digital-to-analog converter 260 converts the digital representations into analog signals for transmission through a communications channel(s) of a transmission medium 265 (analogous to the twisted pair wire 125 illustrated and described with respect to the telecommunications network 100 of FIGURE 1). The digital-to-analog converter 260 also performs other assorted analog processing functions.

100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
73
72
71
70
69
68
67
66
65
64
63
62
61
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

At the receiving end (e.g., the remote terminal hub 130 of the telecommunications network 100 illustrated and described with respect to FIGURE 1) of the transmission medium 265, an analog-to-digital converter 270 of a receiver performs various functions upon the analog signals, such as filtering, and then converts the signals into a digital format. The digital signals are then subjected to an equalization and demodulation subsystem 280, which perform data conditioning tasks and extraction tasks. The equalization operation substantially compensates for signal deterioration associated with the imperfections in the transmission of the signals across the telecommunications network. The equalization and demodulation subsystem 280 also digitally demodulates the conditioned data. The demodulation operation generally occurs to extract information from a carrier signal or signals associated with the transfer of the information across the transmission medium 265.

In the illustrated embodiment, information associated with the transmitted symbols is extracted from Discrete Multi-Tone (DMT), or multiple QAM carrier signals, and the information associated with the symbols is then processed by a bit extractor 285. The bit extractor 285 uses the symbol's constellation (determined by the type of modulation and the number of bits loaded) as a basis for interpreting the values that the symbol represents. The symbol

constellation of the transmitted information (i.e., the symbols) may be determined through such means as synchronized time slicing through application of the bit extractor 285, or other methods of synchronization as devised by those skilled in the art.

5 The extracted bits are then input into an error correction decoding subsystem 290. The error correction decoding then commences, using assorted error correction coding algorithms. The decoded bits are then input into a deframer subsystem 295, which takes the decoded bits and after performing various forms of manipulation, sends the data signals to a data bit sink subsystem 297 and the voice signals to a voice bit sink subsystem 299. The data and voice bit sink subsystems 297, 299 then provide an interface to terminal devices such as the computer terminals 150 and voice terminals 140, respectively, of the telecommunications network 100 illustrated and described with respect to FIGURE 1.

10
15
20

It should be understood that the representative transmitter and receiver are submitted for illustrative purposes only and other configurations (including a design that incorporates the transmitter and receiver sections into an integrated device) compatible with the principles of the present invention may be employed as the application dictates.

Turning now to FIGURE 3, illustrated is a block diagram of an embodiment of channel optimization system 300 constructed according

to the principles of the present invention. The channel optimization system 300 may be embodied in portions of a transmitter (e.g., the bit-to-symbol mapping subsystem 240 illustrated and described with respect to FIGURE 2) and a receiver 5 (e.g., the bit extractor 285 illustrated and described with respect to FIGURE 2).

The channel optimization system 300 includes an assorter 310 that receives and separates signals (e.g., first and second signals such as voice and data signals) and a translator 315. The received signals are parsed according to certain criterions by, for instance, checking timing or information embodied in a merged signal header associated with information entering the assorter 310. More specifically, the parsing subsystem 311 checks the timing boundary of the input signal or extracts control information to determine bits to be selected corresponding to the appropriate constellation density (e.g., voice signals or data signals) of the merged signals. A bit selector 313 of the assorter 310 then uses a value of the output of the parsing subsystem 311 to select and extract the appropriate number of bits, corresponding to a 20 constellation point, in the merged stream. The extracted bits are then input from the assorter 310 into the translator 315. The translator 315 then transforms, or "maps", the associated data and

voice bits received from the assorter 310 into corresponding symbols.

The translator 315 includes a map table evoker 317 and a dynamic table of bit-to-symbol converter 318. The number of bits for either the voice or the data signals are determined by SNR calculation during initialization (see FIGURE 5 and the related description below). The map table evoker 317 determines an appropriate table to evoke for the bit-to-symbol converter 318. The dynamic table of bit-to-symbol converter 318 then selects this appropriate table and performs a bit value to symbol conversion. The bit value to symbol conversion is generally performed in accordance with a symbol density conversion table as set forth below and illustrated in FIGURE 4.

Input bits	Equivalent integer	Output Symbol
0000	0	(1,1)
0001	1	(1,3)
0010	2	(3,1)
0011	3	(3,3)
0100	4	(1,-3)
0101	5	(1,-1)
0110	6	(3,-3)
0111	7	(3,-1)
1000	8	(-3,1)
1001	9	(-3,3)
1010	10	(-1,1)
1011	11	(-1,3)
1100	12	(-3,-3)

1101	13	(-3 , -1)
1110	14	(-1 , -3)
1111	15	(-1 , -1)

5

TABLE 2

The above table is an example of a bit-to-symbol mapping/conversion table for 4 bits with a corresponding constellation. The output symbols can also be represented as complex numbers such 10 as $1+j1$, $-3-j3$, etc. Please note that the equivalent integer values denoted in the middle column do not need to be stored. It is listed to demonstrate the correspondence from the table to the constellation points. Tables for other numbers of bits, from a certain minimum to "Nmax", may also be used in accordance with the principles of the present invention. "Nmax" may be generally defined as a maximum number of bits per symbol that may be supported for transmission by a telecommunications network (e.g., for a DSL-based system, the value may be 8-15).

The mapping may be accomplished by using appropriate 20 implementations of a modulation technique (such as DMT, QAM or the Carrierless AM/PM System known as "CAP", a variation of QAM) as a function of the SNR or SNR gap characteristics of a communications channel or subchannel, and the BER associated with the information traversing the communications channel as described above.

10
9
8
7
6
5
4
3
2
1
0

Typically, the signals that can accommodate a higher BER (e.g., 10^{-3}) are directed to a high symbol density conversion table and the signals necessitating a lower BER (e.g., 10^{-7}) are directed to a low symbol density conversion table. For instance, the voice data most probably will be directed to the high symbol density conversion table and the data signals will be directed to the low symbol density conversion table. By mapping the signals in accordance with their transmission requirements, more information can be inserted on a communications channel to more efficiently utilize the bandwidth thereof.

In connection with a channel optimization system, a plurality of sub-channels of a transmission medium may be used to enhance bandwidth utilization for telecommunications network employing a DMT signaling system. The different sub-channels accommodating differing symbol densities will be more clearly illustrated with respect to an example described with reference to FIGURES 6A, 6B and 6C below.

20

For the case of the DMT-based system, which enables the use of sub-channels of a transmission medium substantially through the use of carrier or signal frequency selectivity, each sub-channel generally employs a distinct carrier frequency. Therefore, each sub-carrier will also have its own distinct carrier frequency which affects the channel capacity of the sub-channel. Each separate

100% DESIGNER'S
150% DESIGNER'S
200% DESIGNER'S

carrier frequency for a given sub-channel and its associated information is substantially processed according to the requirements of a certain application, but the signal output of each sub-channel is ultimately aggregated. The combined signal is 5 then received by a receiver, for instance, a remote terminal hub (such as the remote terminal hub 130 of the telecommunications network 100 illustrated and described in respect to Figure 1.) The remote terminal hub then frequency de-multiplexes the signal based on, for instance, Fourier transforms and then processes each separate sub-channel's carrier wave and associated information substantially in accordance with the receiver.

20

Turning now to FIGURE 5A, illustrated is a flow diagram of an embodiment of an initialization of a channel optimization system (e.g., DMT channel optimization system) in accordance with the principles of the present invention. For the purpose of illustration, an example of signal throughput employing DMT, using separate sub-channels for voice and data signals, will hereinafter be described. One group of sub-channels (designated lower SNR sub-channels) will accommodate voice signals, requiring a higher BER of 10⁻³, and the remaining group of sub-channels (designated higher SNR sub-channels) will accommodate data signals, which require a lower BER of 10⁻⁷.

10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95

Once initialization has started at a step 501, all of the tones should be reordered according to their SNR, from the lowest SNR to the highest SNR, according to a step 503. In conjunction therewith, the sub-channels with similar measured SNR values will 5 be loaded according to a lowest designated index number. An appropriate symbol mapping table with the maximum symbol density allowable for each tone is then stored in a memory of the DMT channel optimization system, according to a step 505, perhaps in a manner analogous to the map table evoker 317 illustrated and described with respect to FIGURE 3. This is the end of the initialization of the DMT channel optimization system, according to a step 507.

20

Turning now to FIGURE 5B, illustrated is a flow diagram of an operation of an embodiment of a channel optimization system (e.g., a DMT channel optimization system) in accordance with the principles of the present invention. Once operation of the DMT channel optimization system has started at a step 510, a data frame is received by the DMT channel optimization system, according to a step 515. The receipt of a data frame by the DMT channel optimization system may be analogous to the operation described with respect to the assorter 310 of the channel optimization system 300 of FIGURE 3, which receives and separates signals for the translator 315 of the channel optimization system 300 of FIGURE 3.

The DMT channel optimization system separates the voice signal bits from the data signal bits, according to a step 520. The DMT channel optimization system then seizes an unloaded tone with the lowest SNR from the tones that are still remaining, according to a
5 step 525.

The DMT channel optimization system then determines if there are any unloaded voice signal bits left from the data frame, according to a step 530. If there are any voice signal bits left, the number of bits per symbol should then be calculated using the voice signal's lower "SNR gap", according to a step 540. Again, each tone is assigned a final mapping table, perhaps in a manner analogous to the map table evoker 317 associated with FIGURE 3. However, the symbol density for the voice signal should be a value that does not exceed the maximum value allowable for symbol density, which was stored in the step 505 associated with the initialization process described in accordance with FIGURE 5A.
10
15
20 Afterwards, the appropriate number of bits is actually loaded to a symbol of that tone, according to a step 550. This loading is perhaps analogous to functions of the bit selector 313 and the bit-to-symbol converter 318 associated with FIGURE 3.

From the step 550, the step of loading the actual bits to the given tone as described above, the DMT channel optimization system again seizes an unloaded tone with the lowest SNR from the tones

that are still remaining, according to the step 525. The DMT channel optimization system again determines if there are any unloaded voice signal bits left from the received data frame, according to the step 530. If there are any unloaded voice signal 5 bits remaining from the received data frame, the DMT channel optimization system simply repeats the step 540 and its associated processes, as detailed above.

However, if the DMT channel optimization system determines in the step 530 that there are no unloaded voice signal bits, then the 10 DMT channel optimization system continues instead to a step 560. In the step 560, the DMT channel optimization system then determines if there are any unloaded data signal bits remaining from the received data frame. If there are no unloaded data signal bits, then the loading of the DMT channel optimization system terminates according to a step 590.

If there are any unloaded data signal bits left to load to a tone, the number of bits per symbol should then be calculated by the DMT channel optimization system using the data signal's higher "SNR gap", according to a step 570. In other words, each tone is 20 assigned a final mapping table, perhaps in a manner analogous to the map table evoker 317 associated with FIGURE 3. Again, this symbol density for the data signal may be a value that does not exceed the maximum symbol density value, which was stored in the

step 505 associated with the initialization process described in accordance with FIGURE 5A. Then the appropriate number of bits is actually loaded to a symbol of that tone, according to a step 580. Again, this loading is perhaps analogous to functions of the bit 5 selector 313 and the bit-to-symbol converter 318 associated with FIGURE 3.

10
0
9
8
7
6
5
4
3
2
1
0

Afterwards, the DMT channel optimization system again seizes an unloaded tone with the lowest SNR from among the tones that are left, according to the step 525. The DMT channel optimization system once again determines if there are any unloaded voice signal bits left from the data frame, according to the step 530.

In connection with the signal processing, the transmitting and receiving ends are concurrently synchronized to share relevant information pertaining to voice and data signal separation. Those skilled in the art understand that other methods to separate the voice and data signals and synchronize the endpoints are well within the broad scope of the present invention.

20

Also for the purposes of illustration, an example is hereinafter described in the environment of a multi-channel/sub-channel telecommunications network using a signaling system, such as DMT. The utilization of the bandwidth of the telecommunications network is improved when voice and data signals of differing BER

requirements are separated, and then directed to specific sub-channels with different SNRs.

For a DSL G.Lite (G.992.2) based system (see ITU-T. G.992.2 "Splitterless Asymmetric Digital Subscriber Line Transceivers",
5 June 1999, which is incorporated herein by reference), the downstream transmission is considered. It is assumed that the signal is transmitted via the loop model of T1.601 number 2, (see ANSI T1.601-1998, "Integrated Services Digital Network Basic Access Interface for Use on Metallic Loops for Application on the Network Side of the NT," layer 1 specification, which is incorporated herein by reference). The interference is 24 self Near End Crosstalk (NEXT) noise and 24 self Far End Crosstalk (FEXT) noise (providing 24 adjacent loops with same service in the same bundle group). It is also assumed that the margin equals the CodingGain
10 at about 6 db.
15

If voice and data signals are not separated and are all merely loaded to the sub-channels 33-128 (see FIGURE 4A) based on a uniform SNR gap of 9.77 db (for a BER of 10^{-7}), 169 bits can be transmitted. With a symbol rate of 4000 symbols/second, the bit rate is 676,000 bits-per-second. If 256,000 bits-per-second are needed to transmit the voice signals, the bandwidth available for data signals is 420,000 bits-per-second.
20

If the voice signals, however, are separated from the data signals, the voice sub-channel's constellation and symbol density (the modulation technique of QAM is being used for each sub-carrier) is calculated with a SNR gap of 5.56 db. Through the use
5 of loading in accordance with the principles of the present invention, instead of designing for a 9.77 db SNR gap (under uniform treatment of voice and data signals), the sub-channel capacity for the voice signals has increased. Using the above values and substituting them into the various equations given earlier, the remaining channel bandwidth left for the data signals will be about 548,1000 bits-per-second, leading to an increased utilization of the bandwidth. This is 128,000 bits-per-second more signal throughput than the 420,000 bits-per-second bandwidth that was available previously.

10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
205
210
215
220
225
230
235
240
245
250
255
260
265
270
275
280
285
290
295
300
305
310
315
320
325
330
335
340
345
350
355
360
365
370
375
380
385
390
395
400
405
410
415
420
425
430
435
440
445
450
455
460
465
470
475
480
485
490
495
500
505
510
515
520
525
530
535
540
545
550
555
560
565
570
575
580
585
590
595
600
605
610
615
620
625
630
635
640
645
650
655
660
665
670
675
680
685
690
695
700
705
710
715
720
725
730
735
740
745
750
755
760
765
770
775
780
785
790
795
800
805
810
815
820
825
830
835
840
845
850
855
860
865
870
875
880
885
890
895
900
905
910
915
920
925
930
935
940
945
950
955
960
965
970
975
980
985
990
995
1000
1005
1010
1015
1020
1025
1030
1035
1040
1045
1050
1055
1060
1065
1070
1075
1080
1085
1090
1095
1100
1105
1110
1115
1120
1125
1130
1135
1140
1145
1150
1155
1160
1165
1170
1175
1180
1185
1190
1195
1200
1205
1210
1215
1220
1225
1230
1235
1240
1245
1250
1255
1260
1265
1270
1275
1280
1285
1290
1295
1300
1305
1310
1315
1320
1325
1330
1335
1340
1345
1350
1355
1360
1365
1370
1375
1380
1385
1390
1395
1400
1405
1410
1415
1420
1425
1430
1435
1440
1445
1450
1455
1460
1465
1470
1475
1480
1485
1490
1495
1500
1505
1510
1515
1520
1525
1530
1535
1540
1545
1550
1555
1560
1565
1570
1575
1580
1585
1590
1595
1600
1605
1610
1615
1620
1625
1630
1635
1640
1645
1650
1655
1660
1665
1670
1675
1680
1685
1690
1695
1700
1705
1710
1715
1720
1725
1730
1735
1740
1745
1750
1755
1760
1765
1770
1775
1780
1785
1790
1795
1800
1805
1810
1815
1820
1825
1830
1835
1840
1845
1850
1855
1860
1865
1870
1875
1880
1885
1890
1895
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
2110
2115
2120
2125
2130
2135
2140
2145
2150
2155
2160
2165
2170
2175
2180
2185
2190
2195
2200
2205
2210
2215
2220
2225
2230
2235
2240
2245
2250
2255
2260
2265
2270
2275
2280
2285
2290
2295
2300
2305
2310
2315
2320
2325
2330
2335
2340
2345
2350
2355
2360
2365
2370
2375
2380
2385
2390
2395
2400
2405
2410
2415
2420
2425
2430
2435
2440
2445
2450
2455
2460
2465
2470
2475
2480
2485
2490
2495
2500
2505
2510
2515
2520
2525
2530
2535
2540
2545
2550
2555
2560
2565
2570
2575
2580
2585
2590
2595
2600
2605
2610
2615
2620
2625
2630
2635
2640
2645
2650
2655
2660
2665
2670
2675
2680
2685
2690
2695
2700
2705
2710
2715
2720
2725
2730
2735
2740
2745
2750
2755
2760
2765
2770
2775
2780
2785
2790
2795
2800
2805
2810
2815
2820
2825
2830
2835
2840
2845
2850
2855
2860
2865
2870
2875
2880
2885
2890
2895
2900
2905
2910
2915
2920
2925
2930
2935
2940
2945
2950
2955
2960
2965
2970
2975
2980
2985
2990
2995
3000
3005
3010
3015
3020
3025
3030
3035
3040
3045
3050
3055
3060
3065
3070
3075
3080
3085
3090
3095
3100
3105
3110
3115
3120
3125
3130
3135
3140
3145
3150
3155
3160
3165
3170
3175
3180
3185
3190
3195
3200
3205
3210
3215
3220
3225
3230
3235
3240
3245
3250
3255
3260
3265
3270
3275
3280
3285
3290
3295
3300
3305
3310
3315
3320
3325
3330
3335
3340
3345
3350
3355
3360
3365
3370
3375
3380
3385
3390
3395
3400
3405
3410
3415
3420
3425
3430
3435
3440
3445
3450
3455
3460
3465
3470
3475
3480
3485
3490
3495
3500
3505
3510
3515
3520
3525
3530
3535
3540
3545
3550
3555
3560
3565
3570
3575
3580
3585
3590
3595
3600
3605
3610
3615
3620
3625
3630
3635
3640
3645
3650
3655
3660
3665
3670
3675
3680
3685
3690
3695
3700
3705
3710
3715
3720
3725
3730
3735
3740
3745
3750
3755
3760
3765
3770
3775
3780
3785
3790
3795
3800
3805
3810
3815
3820
3825
3830
3835
3840
3845
3850
3855
3860
3865
3870
3875
3880
3885
3890
3895
3900
3905
3910
3915
3920
3925
3930
3935
3940
3945
3950
3955
3960
3965
3970
3975
3980
3985
3990
3995
4000
4005
4010
4015
4020
4025
4030
4035
4040
4045
4050
4055
4060
4065
4070
4075
4080
4085
4090
4095
4100
4105
4110
4115
4120
4125
4130
4135
4140
4145
4150
4155
4160
4165
4170
4175
4180
4185
4190
4195
4200
4205
4210
4215
4220
4225
4230
4235
4240
4245
4250
4255
4260
4265
4270
4275
4280
4285
4290
4295
4300
4305
4310
4315
4320
4325
4330
4335
4340
4345
4350
4355
4360
4365
4370
4375
4380
4385
4390
4395
4400
4405
4410
4415
4420
4425
4430
4435
4440
4445
4450
4455
4460
4465
4470
4475
4480
4485
4490
4495
4500
4505
4510
4515
4520
4525
4530
4535
4540
4545
4550
4555
4560
4565
4570
4575
4580
4585
4590
4595
4600
4605
4610
4615
4620
4625
4630
4635
4640
4645
4650
4655
4660
4665
4670
4675
4680
4685
4690
4695
4700
4705
4710
4715
4720
4725
4730
4735
4740
4745
4750
4755
4760
4765
4770
4775
4780
4785
4790
4795
4800
4805
4810
4815
4820
4825
4830
4835
4840
4845
4850
4855
4860
4865
4870
4875
4880
4885
4890
4895
4900
4905
4910
4915
4920
4925
4930
4935
4940
4945
4950
4955
4960
4965
4970
4975
4980
4985
4990
4995
5000
5005
5010
5015
5020
5025
5030
5035
5040
5045
5050
5055
5060
5065
5070
5075
5080
5085
5090
5095
5100
5105
5110
5115
5120
5125
5130
5135
5140
5145
5150
5155
5160
5165
5170
5175
5180
5185
5190
5195
5200
5205
5210
5215
5220
5225
5230
5235
5240
5245
5250
5255
5260
5265
5270
5275
5280
5285
5290
5295
5300
5305
5310
5315
5320
5325
5330
5335
5340
5345
5350
5355
5360
5365
5370
5375
5380
5385
5390
5395
5400
5405
5410
5415
5420
5425
5430
5435
5440
5445
5450
5455
5460
5465
5470
5475
5480
5485
5490
5495
5500
5505
5510
5515
5520
5525
5530
5535
5540
5545
5550
5555
5560
5565
5570
5575
5580
5585
5590
5595
5600
5605
5610
5615
5620
5625
5630
5635
5640
5645
5650
5655
5660
5665
5670
5675
5680
5685
5690
5695
5700
5705
5710
5715
5720
5725
5730
5735
5740
5745
5750
5755
5760
5765
5770
5775
5780
5785
5790
5795
5800
5805
5810
5815
5820
5825
5830
5835
5840
5845
5850
5855
5860
5865
5870
5875
5880
5885
5890
5895
5900
5905
5910
5915
5920
5925
5930
5935
5940
5945
5950
5955
5960
5965
5970
5975
5980
5985
5990
5995
6000
6005
6010
6015
6020
6025
6030
6035
6040
6045
6050
6055
6060
6065
6070
6075
6080
6085
6090
6095
6100
6105
6110
6115
6120
6125
6130
6135
6140
6145
6150
6155
6160
6165
6170
6175
6180
6185
6190
6195
6200
6205
6210
6215
6220
6225
6230
6235
6240
6245
6250
6255
6260
6265
6270
6275
6280
6285
6290
6295
6300
6305
6310
6315
6320
6325
6330
6335
6340
6345
6350
6355
6360
6365
6370
6375
6380
6385
6390
6395
6400
6405
6410
6415
6420
6425
6430
6435
6440
6445
6450
6455
6460
6465
6470
6475
6480
6485
6490
6495
6500
6505
6510
6515
6520
6525
6530
6535
6540
6545
6550
6555
6560
6565
6570
6575
6580
6585
6590
6595
6600
6605
6610
6615
6620
6625
6630
6635
6640
6645
6650
6655
6660
6665
6670
6675
6680
6685
6690
6695
6700
6705
6710
6715
6720
6725
6730
6735
6740
6745
6750
6755
6760
6765
6770
6775
6780
6785
6790
6795
6800
6805
6810
6815
6820
6825
6830
6835
6840
6845
6850
6855
6860
6865
6870
6875
6880
6885
6890
6895
6900
6905
6910
6915
6920
6925
6930
6935
6940
6945
6950
6955
6960
6965
6970
6975
6980
6985
6990
6995
7000
7005
7010
7015
7020
7025
7030
7035
7040
7045
7050
7055
7060
7065
7070
7075
7080
7085
7090
7095
7100
7105
7110
7115
7120
7125
7130
7135
7140
7145
7150
7155
7160
7165
7170
7175
7180
7185
7190
7195
7200
7205
7210
7215
7220
7225
7230
7235
7240
7245
7250
7255
7260
7265
7270
7275
7280
7285
7290
7295
7300
7305
7310
7315
7320
7325
7330
7335
7340
7345
7350
7355
7360
7365
7370
7375
7380
7385
7390
7395
7400
7405
7410
7415
7420
7425
7430
7435
7440
7445
7450
7455
7460
7465
7470
7475
7480
7485
7490
7495
7500
7505
7510
7515
7520
7525
7530
7535
7540
7545
7550
7555
7560
7565
7570
7575
7580
7585
7590
7595
7600
7605
7610
7615
7620
7625
7630
7635
7640
7645
7650
7655
7660
7665
7670
7675
7680
7685
7690
7695
7700
7705
7710
7715
7720
7725
7730
7735
7740
7745
7750
7755
7760
7765
7770
7775
7780
7785
7790
7795
7800
7805
7810
7815
7820
7825
7830
7835
7840
7845
7850
7855
7860
7865
7870
7875
7880
7885
7890
7895
7900
7905
7910
7915
7920
7925
7930
7935
7940
7945
7950
7955
7960
7965
7970
7975
7980
7985
7990
7995
8000
8005
8010
8015
8020
8025
8030
8035
8040
8045
8050
8055
8060
8065
8070
8075
8080
8085
8090
8095
8100
8105
8110
8115
8120
8125
8130
8135
8140
8145
8150
8155
8160
8165
8170
8175
8180
8185
8190
8195
8200
8205
8210
8215
8220
8225
8230
8235
8240
8245
8250
8255
8260
8265
8270
8275
8280
8285
8290
8295
8300
8305
8310
8315
8320
8325
8330
8335
8340
8345
8350
8355
8360
8365
8370
8375
8380
8385
8390
8395
8400
8405
8410
8415
8420
8425
8430
8435
8440
8445
8450
8455
8460
8465
8470
8475
8480
8485
8490
8495
8500
8505
8510
8515
8520
8525
8530
8535
8540
8545
8550
8555
8560
8565
8570
8575
8580
8585
8590
8595
8600
8605
8610
8615
8620
8625
8630
8635
8640
8645
8650
8655
8660
8665
8670
8675
8680
8685
8690
8695
8700
8705
8710
8715
8720
8725
8730
8735
8740
8745
8750
8755
8760
8765
8770
8775
8780
8785
8790
8795
8800
8805
8810
8815
8820
8825
8830
8835
8840
8845
8850
8855
8860
8865
8870
8875
8880
8885
8890
8895
8900
8905
8910
8915
8920
8925
8930
8935
8940
8945
8950
8955
8960
8965
8970
8975
8980
8985
8990
8995
9000
9005
9010
9015
9020
9025
9030
9035
9040
9045
9050
9055
9060
9065
9070
9075
9080
9085
9090
9095
9100
9105
9110
9115
9120
9125
9130
9135
9140
9145
9150
9155
9160
9165
9170
9175
9180
9185
9190
9195
9200
9205
9210
9215
9220
9225
9230
9235
9240
9245
9250
9255
9260
9265
9270
9275
9280
9285
9290
9295
9300
9305
9310
9315
9320
9325
9330
9335
9340
9345
9350
9355
9360
9365
9370
9375
9380
9385
9390
9395
9400
9405
9410
9415
9420
9425
9430
9435
9440
9445
9450
9455
9460
9465
9470
947

separated. In FIGURE 6C, the diamond terminated sub-channels are loaded with the voice signals, while the circular terminated sub-channels are loaded with data signals.

It can be observed by comparing FIGURE 6B, illustrating conventional techniques, and FIGURE 6C, illustrating the principles of the present invention, that the sub-channels with a low SNR at the far ends are simply wasted by the conventional loading method.

In this particular example, the system of the present invention loaded 10 bits to previously unused sub-channels, or 40,000 bits-per-second for the voice signals. It is also observed from FIGURE 6C that usually one more bit can be added to each sub-channel if the voice signals are loaded instead of the data signals, also leading to increased utilization of the bandwidth of the telecommunications network.

It should be understood, that the embodiments of the channel optimization system constructed according to the principles of the present invention illustrated and described with respect to the preceding FIGURES are submitted for illustrative purposes only and other configurations compatible with the principles of the present invention may be employed as the application dictates. Also, it should be understood that the systems and subsystems associated with the present invention may be embodied in software, dedicated

or hardwired discrete or integrated circuitry, or combinations thereof.

Finally, for a better understanding of digital communications, in general, "Digital Communications," by Edward A. Lee and David G. Messerschmitt, Kluwer Academic Publishers (1994) and "Digital Communications," by John Proakis, McGraw-Hill, 3rd Edition (1995) and in reference to Digital Subscriber Line Services including the standards and systems that support the technology, see "Understanding Digital Subscriber Line Technology," by Thomas Starr, Peter Silverman, and John M. Coiffi, Prentice Hall (1998), each of which is incorporated herein by reference.

Although the present invention has been described in detail, those skilled in the art should understand that they can make various changes, substitutions and alterations herein without departing from the spirit and scope of the invention in its broadest form.